Effect of Flashes of Light on Night Visual Acuity

Part I

Prepared by

Glenn A. Fry and Mathew Alpern
Ohio State University Research Foundation

Published by the Armed Forces - National Research Council
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INTRODUCTION

The purpose of this study is to find out the ability of the eye to see a dark object against a sky background at night after the eye has been exposed to a flash of light, or a series of flashes. In this study the pattern illustrated in Fig. 1 has been used to measure the ability of the eye to see. Using his right eye only, the subject looks at the red fixation point (A) and this brings the test object (B) to fall 5° to the right of the principal line of sight. B is a disc having a brightness in most of the experiments equal to 0.0107 millilambert and when such a surface is viewed through a 2 mm. artificial pupil, as was the case in the experiments to follow, the retinal illumination (0.107 troland) is equivalent to that produced by a moonlit sky. The black bar extending vertically across the center of the disc can be varied in width to measure the threshold of visibility. By this method it is possible to measure the sensitivity of this part of the retina while keeping it exposed to a constant background brightness.

If a flash of light directly stimulates that region of the retina which is to be tested, it will affect directly the adaptation of the photoreceptors in that region, and in order to investigate the effect of such a direct exposure the following procedure was used. While the eye fixated the point A, the disc-shaped area (B) had superimposed upon it a patch of brightness of the same size and shape as B and then, while the eye continued to fixate A, recovery of the stimulated area of the retina was studied by measuring the threshold width of the black bar.

The brightness and duration of these flashes have been investigated, and also the effect of using a multiple number of flashes. An attempt has also been made to evaluate the performance of the eye at lower levels of background brightness than 0.01 millilambert.

Under the conditions of this type of experiment, the exposure of the eye to a flash patch not only impairs the capacity of the photoreceptors to respond to subsequent stimulation but also produces a positive after-image. A complete understanding of the effect of a flash of light cannot be claimed until the role played by this positive after-image is taken into account. When the flash patch is exactly the same size and shape as the test patch, it might be questioned whether small eye movements which cause a fresh portion of the retina to receive a portion of the image of the test patch might affect the results. Consequently, exploratory experiments have been undertaken with much larger flash patches to investigate the role played by this factor.

When the flash patch falls in a different part of the field than the test patch, one of the obvious ways in which the test patch can affect the subsequent response of the eye to the bar is for stray light from the flash patch to cover the region of the retina in which the test patch falls. This adapts that region of the retina to a level of retinal illuminance represented by the stray light. If the effect of a flash patch which does not coincide with or overlap the test patch can be accounted for in terms of stray light in the eye, then the effect of a given distribution of light in a flash in the visual field could be evaluated without an empirical investigation of all the possible brightness distributions which might occur. In order to explore this possibility, flash patches at various distances from the test patch have been used; the effect of area of the test patch has also been investigated as well as the effect of placing the flash patch on the blind spot.

In all of this work, the size of the beam entering the eye has been restricted by artificial pupils which are smaller than the natural pupil, so that variations in the size of the natural pupil have not influenced the results. There are changes in pupil size which occur as a result of a flash of light, but it was decided to study these effects in a separate investigation which will be described in another report.

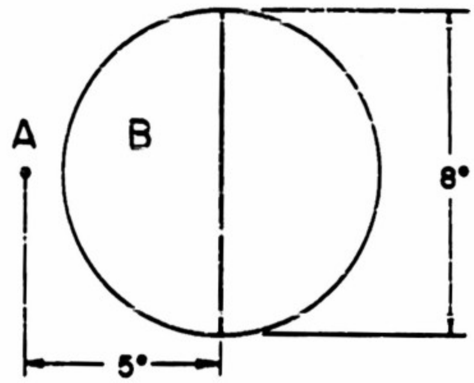


Figure 1. Peripheral Test Object and Fixation Point Used for Measuring the Ability of the Eye to See a Dark Object Against a Sky Background.

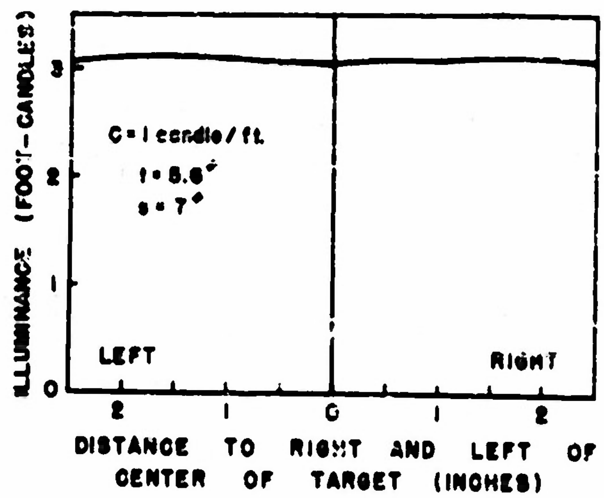


Figure 2. Distribution of the Light Illuminating the Target.

APPARATUS AND PROCEDURE

A. Head Supports

The subject's head was supported by a forehead support and biting board which could be adjusted to put the center of the entrance pupil of the right eye at the point E, in Fig. 3, when this eye is fixating the red fixation point at A_1. Sighting devices not shown in the figure were used in making this adjustment.

B. The Fixation Point.

Light from the small bulb S_1 passes through a red filter and the pin-point aperture A_1, then strikes the small mirror M_1 and is reflected so as to strike the peripheral region of the lens L_1 in such a way that the image of A_1 is seen approximately 5° from the center of the lens L_1 by the right eye of the observer placed with its entrance pupil at the point E. The intensity of the fixation point can be controlled by a rheostat. The mirror image of A_1 falls in the plane of the aperture A_2.

C. The Visual Acuity Measuring Device

The visual acuity target, T, is a vertical black line on a piece of white cardboard, which is illuminated by two line filament sources S_2 the intensity of which can be varied by a rheostat. Considerable care has been exercised in the design of the form of the sources S_2 and their positions with relation to the target in order to maintain uniform illumination on the target. The vertical line filaments of the two sources are long enough so that one can assume that these sources are equivalent to two luminous lines indefinitely extended. Consequently, one can assume that the illumination is constant at points on any given vertical line across the target. Assuming that the two luminous lines are indefinitely extended the illuminance (I) in foot-candles at any given point P at a distance v from the perpendicular line through the center of the target is as follows:

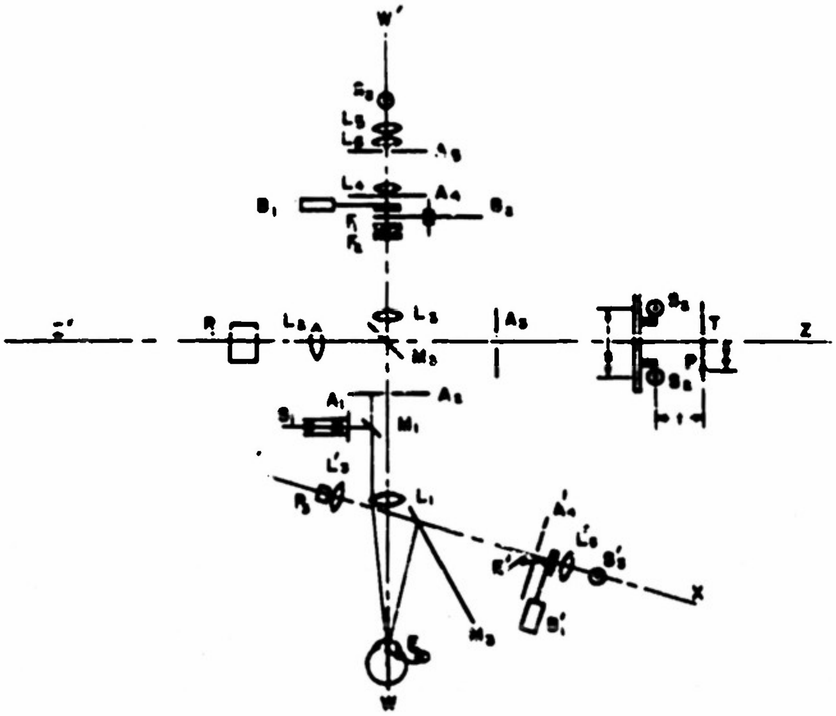


Figure 3. Apparatus

$$I = 4\,Ct \left[\frac{1}{t^2 + \left(\frac{s}{2} + V\right)^2} + \frac{1}{t^2 + \left(\frac{s}{2} - V\right)^2} \right] \qquad (1)$$

where s represents the distance between the two sources, and t represents the perpendicular distance of each source from the screen and C represents the candlepower per foot of filament length, and where all distances in the equation are expressed in feet. Fig. 2 shows the distribution of illuminance along the horizontal diameter of the disc when C = 1 candle per foot, when s = 7 in. and t = 5.6 in. The target and two sources are all mounted on a trolley which moves along a track, which keeps the target centered on the axis ZZ'. Light from this target passes through the aperture A_5 above the mirror M_2 to the lens L_2. After passing through the lens L_2 the light passes through the Porro prism P_1 to be reflected by the semi-silvered mirror M_2. The Porro prism is also mounted on

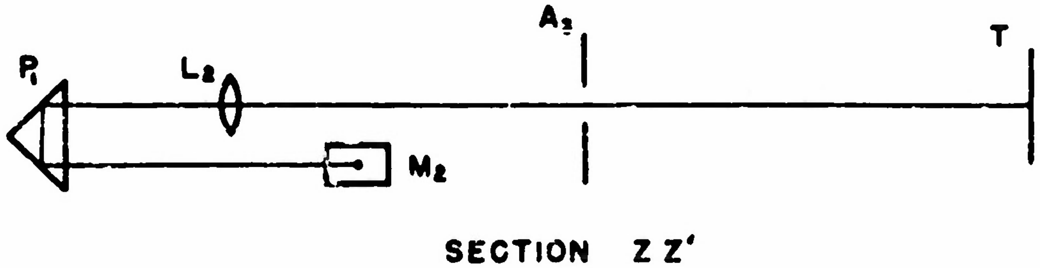


Figure 4. A Vertical Section Showing Part of the Apparatus in Figure 3.

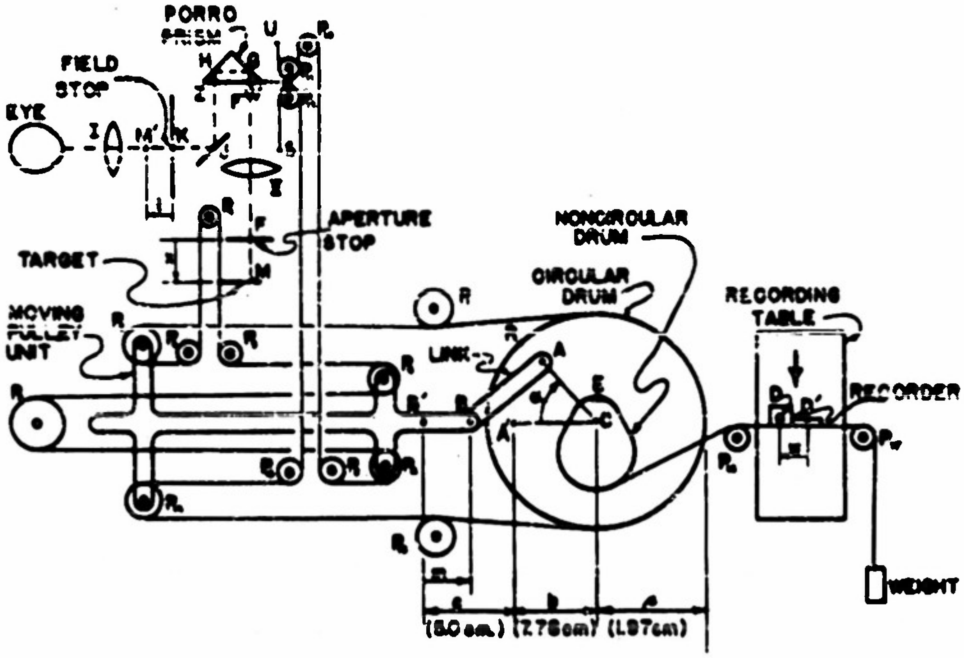


Figure 5. Mechanism for (1) Changing the Visual Angle Subtended by the Bar and (2) Recording the Data.

a trolley which moves along the axis ZZ' and this movement is synchronized with that of the target by a special driving mechanism described below which is designed to keep the image of the target formed by lens L_2 in the plane of the aperture A_2. The eye at E sees the image of the target at optical infinity and magnified to a variable degree depending on the position of the target. A vertical section of this system along the line ZZ' is illustrated in Fig. 4.

The angle subtended by the test object at the aperture A_3 is equal to the angle subtended by the image of the target as seen by the eye at E since the lenses L_1 and L_2 have the same focal length; since the distance from E to L_1 is equal to the focal length of L_1; and since the distance from A_3 to L_2 is equal to the focal length of L_2. This relation simplifies the computation of the angular size of the image of the bar at the entrance pupil of the eye.

The driving mechanism designed to synchronize the movement of the target and the Porro prism is shown in Fig. 5. In this figure the target M corresponds to the target T in Fig. 3. The aperture stop F corresponds to aperture A_3, the Porro prism corresponds to the Porro prism P_1, the field stop K corresponds to the aperture A_2, the mirror J corresponds

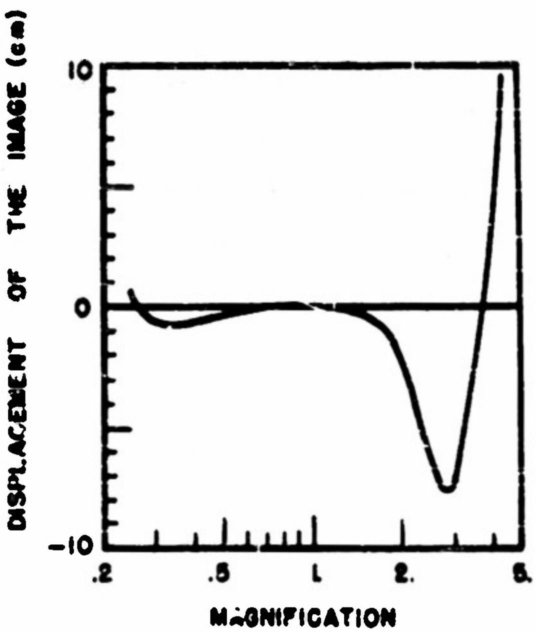


Figure 6. Extent to Which the Image M' is Displaced in Front of (+) or Behind (-) the Plane of the Field Stop, K.

to the mirror M_2 and the lenses I and II correspond to L_2 and L_1. The pulleys P_4, P_3, P_5, P_7, P_{13}, P_{10}, P_9, P_1 and P_{15} are mounted on axles which are fixed to the instrument. Pulleys P_2, P_6, P_8, and P_{14} are mounted on axles fixed to the moving pulley unit. Pulleys P_{11} and P_{12} are mounted on axles which are fixed to the trolley carrying the Porro prism. The position of the Porro prism is controlled by means of two flexible cables. One of these cables wraps around P_{12} and connects the point S, which is fixed with respect to the instrument, with the point R on the circular drum. The second cable wraps around pulley P_{11} and connects the fixed point U with the point R on the circular drum. The target M is connected to the flexible cable which connects the point U with the point R. The circular drum is mounted on a shaft which is geared to a crank controlled by the operator. When this circular drum moves in a clockwise direction through an angle α, it takes up a certain amount of the flexible cable UR and releases the same amount of the cable SR. The link which connects the eccentric point A on the circular drum to the point B on the moving pulley unit moves the point B on the moving pulley unit through a distance m from its starting point B'. The driving mechanism is designed to keep the image M' of the target M in the plane of the field stop K, but the compensation is not perfect and the displacement (t) of M' from K is finite and found by means of the following equation:

$$t = \frac{f^2}{f + 2m - \rho\alpha} - (f + 2m + \rho\alpha), \qquad (2)$$

where f = focal length of lens II (3)

and $$m = b\left[\cos\alpha + \sqrt{\left(\frac{c}{b}\right)^2 - \sin^2\alpha}\,\right] \qquad (4)$$

Defining magnification ϕ as the ratio of the width of the image of the bar at M' to the width of the bar at M,

$$\phi = -\frac{f}{x} = -\frac{f}{f + 2m - \rho\alpha} \qquad (5)$$

Fig. 6 shows the amount of displacement t of M' from K for various values of ϕ.

The field stop K limits the field of view to a circular patch 8° in diameter. The image of the target completely fills this aperture and the dark vertical line through the center of the target appears as a dark vertical bar through the center of the aperture stop giving the appearance shown in Fig. 1. The angular width of this bar at the eye is given by the following equation:

$$\text{Visual angle subtended by the bar at the eye in radians} = \frac{y}{x} \qquad (6)$$

where y represents the width of the black line on the target at M and x represents the distance of the target from the primary focal plane (F) of lens II which is also the aperture stop. All of the data presented in this report except those dealing with low background brightnesses were obtained with a black line 0.5 mm wide.

D. Flash Patch Exposure Devices.

There are three flash patch exposure devices, two of which will be described here and one later in connection with large flash patches.

Device No. 1. This device provides for a flash patch of the same size and position as the test patch. Light from the ribbon filament source S_3 in Fig. 3 is brought to a focus with the lenses L_5, L_6 and L_4 at the aperture A_4 and after passing through the neutral density filters F_1 and F_2 is collimated by the lens L_3, passes through the semi-silvered mirror M_2, the aperture A_2, and is then brought to focus at the center of the entrance pupil of eye E by the lens L_1. The field stop A_2 is also the field stop for the test patch, and consequently the size of the flash patch is the same as that of the test patch. The brightness of the test patch is controlled by means of neutral density filters (F_1 and F_2). The aperture A_4 is 1 mm in diameter and constitutes the aperture stop for the flash patch. An image of the aperture is formed in the plane of the entrance pupil by the lenses L_3 and L_1. This image in the plane of the entrance pupil has the same size as the aperture stop itself. The time of onset and duration of exposure of the flash source is regulated by means of a shutter device which is partly mechanical and partly electromagnetic. It provides exposure durations of 1, 3, 10, 30, 100, 300. 1,000 and 3,000 milliseconds and longer were provided by the electromagnetic part of the shutter which consists of a solenoid with two coils one of which opens the shutter and the second of which closes the shutter. The solenoid coils are controlled by micro-switches activated by cams driven by a constant speed motor. A single manual switch is pushed to turn on the light source S_3 and to start the motor which drives the cams. A second switch is pushed which, when the timing mechanism is first ready after the switch is pushed, gives one complete exposure.

Exposures as short as and shorter than 30 milliseconds are obtained by means of a rotating sectored disc shown in Fig. 7 which is synchronized with the timing mechanism controlling the electromagnetic shutter. It rotates 10 times per second. The electromagnetic shutter is set to give an exposure of 100 milliseconds and during this interval the rotating sectored disc provides an exposure of 30, 10, 3, or 1 milliseconds depending upon which of the open sectors crosses the beam. Each of these exposures starts 50 milliseconds after the electromagnetic shutter opens. The axis of the rotating disc can be swiveled around a second axis parallel to itself so that either one of the four open sectors can be made to cross the beam, or the entire disc can be lifted out of the way of the beam so that the electromagnetic shutter alone controls the exposure.

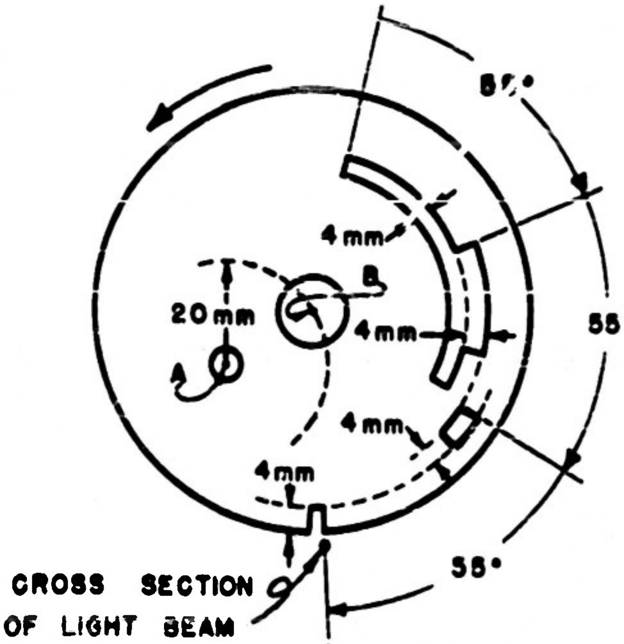
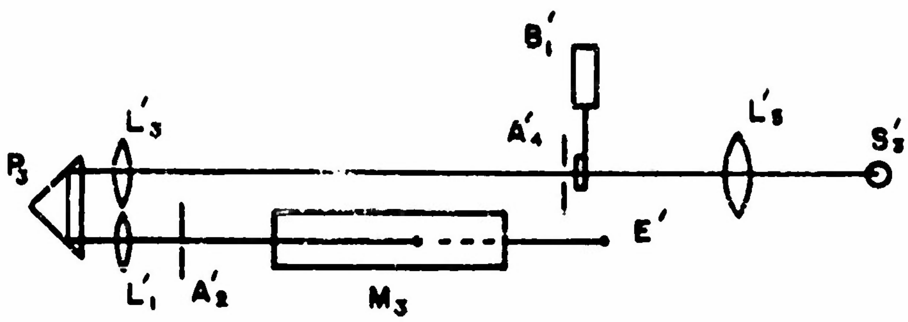


Figure 7. Rotating Sectored Disk for Producing Exposures 1, 3, 10, and 30 Milliseconds Long. The Disk Rotates 10 Times Per Second.

Device No. 2. This device provides for a peripheral flash patch which can be presented to the eye when the eye is held in position for observing the test patch, and hence one can follow through with the presentation of the flash patch and the measurement of the effect of this flash upon the visibility of the bar without changing the position of the head or the eye.

The mechanism for this device is more clearly illustrated in Fig. 8 which is a section view of part of Fig. 3 along the axis XX'. Light from the ribbon filament source S'_3 is focused by the lens L'_5 in the plane of the aperture stop A'_4. After passing through the diaphragm A'_4 the light passes above the mirror M_3, through the lens L'_3, the Porro prism P_3, the lens L'_1, then after reflection at the mirror M_3, it comes to a focus at the center of the entrance pupil E of the observer's eye (Fig. 3). The elements S'_3, A'_4, L'_5, L'_3, L'_1, P_3, B'_1 and A'_2 are mounted on an arm which rotates above the mirror M_3 around E', which is the image of E formed by the mirror M_3. This provides a means for varying



SECTION X X'

Figure 8. Vertical Section Showing part of the Apparatus in Figure 3.

the displacement of the center of the flash patch from the center of the test patch through the range from 8° to 35°, and since this is in the horizontal meridian of the right eye, it affords a unique way of studying the effect of light scattered within the eye including the effect of light striking the blind spot.

The aperture stop A'_4 is 2 mm in diameter and an image of this aperture of the same size is formed by the lenses L'_3 and L'_1 at the center of the entrance pupil.

The aperture A'_2 controls the size and shape of the peripheral flash patch. This is circular and several apertures were used providing diameters subtending visual angles ranging from 2.5° to 0.35°. The electromagnetic shutter B' is identical in type with the electromagnetic shutter B_1 and its onset and duration of exposure is controlled by the same timing mechanism which provides exposures of 100, 300, 1,000 and 3,000 milliseconds.

E. Procedure in Measuring the Effect of a Flash

Preliminary to such a measurement it is necessary to adjust the headrest and the biting board so that when the subject puts his head in the instrument, the entrance pupil of the right eye will fall at the proper point. The subject is dark adapted for 30 minutes in a dark room and than he puts his head in the instrument. His attention is directed to the fixation point which he attempts to fixate steadily during the course of the experiment. Time is allowed for the subject to become bright-adapted to the level of the test spot. When the operator is ready to give the subject a flash he pushes first the switch that starts the recorder, then the switch that starts the timing mechanism and turns on the source for the flash patch, and then the switch that gives the exposure. As soon as the flash is over, he throws the switch which stops the timing mechanism and turns off the source for the flash patch and at the same time marks a line on the record, as will be explained later, which indicates the cessation of the flash. Starting with the minimum width, the width of the bar is increased until it first becomes visible. This width is recorded after which the width is then decreased until the bar becomes invisible and then is increased again until it becomes visible, the width again being recorded. This process is repeated until the threshold width reaches a stable level. The subject is then given a second exposure of a flash involving a different brightness or duration and the process of recording the effect of the flash is repeated.

If immediately after the cessation of the flash the bar is not visible when it is increased to its maximum size, it is left at its maximum size until the subject first reports it to be visible, and then the size is decreased until it becomes invisible, then increased

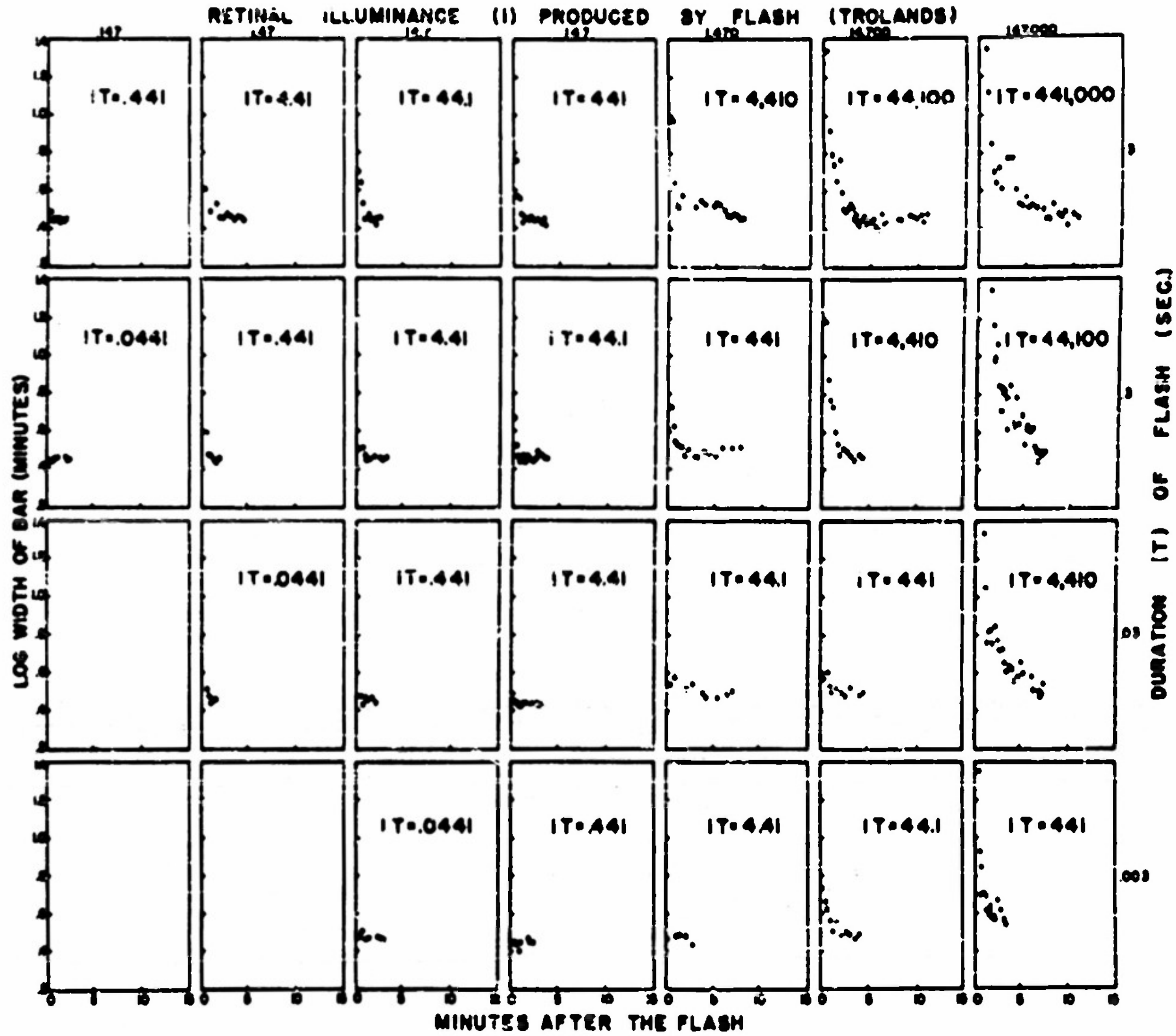


FIG. 9A

RETURN OF VISUAL ACUITY TO NORMAL FOLLOWING FLASHES OF VARIOUS DURATIONS AND BRIGHTENESSES THAT ARE COEXTENSIVE WITH THE TEST SPOT.

DATA FOR R.H.

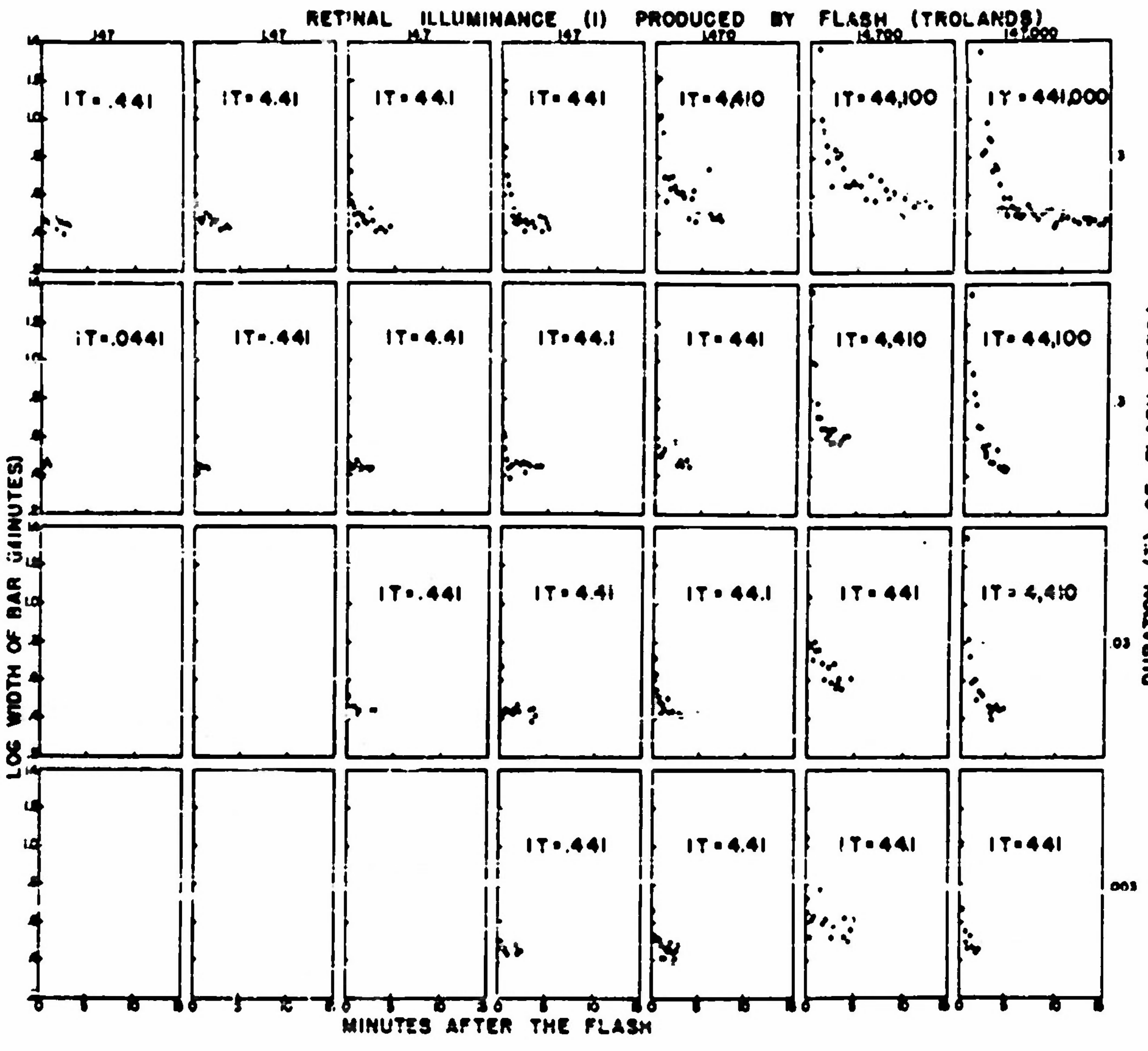


FIG. 9B

DATA FOR M.A.

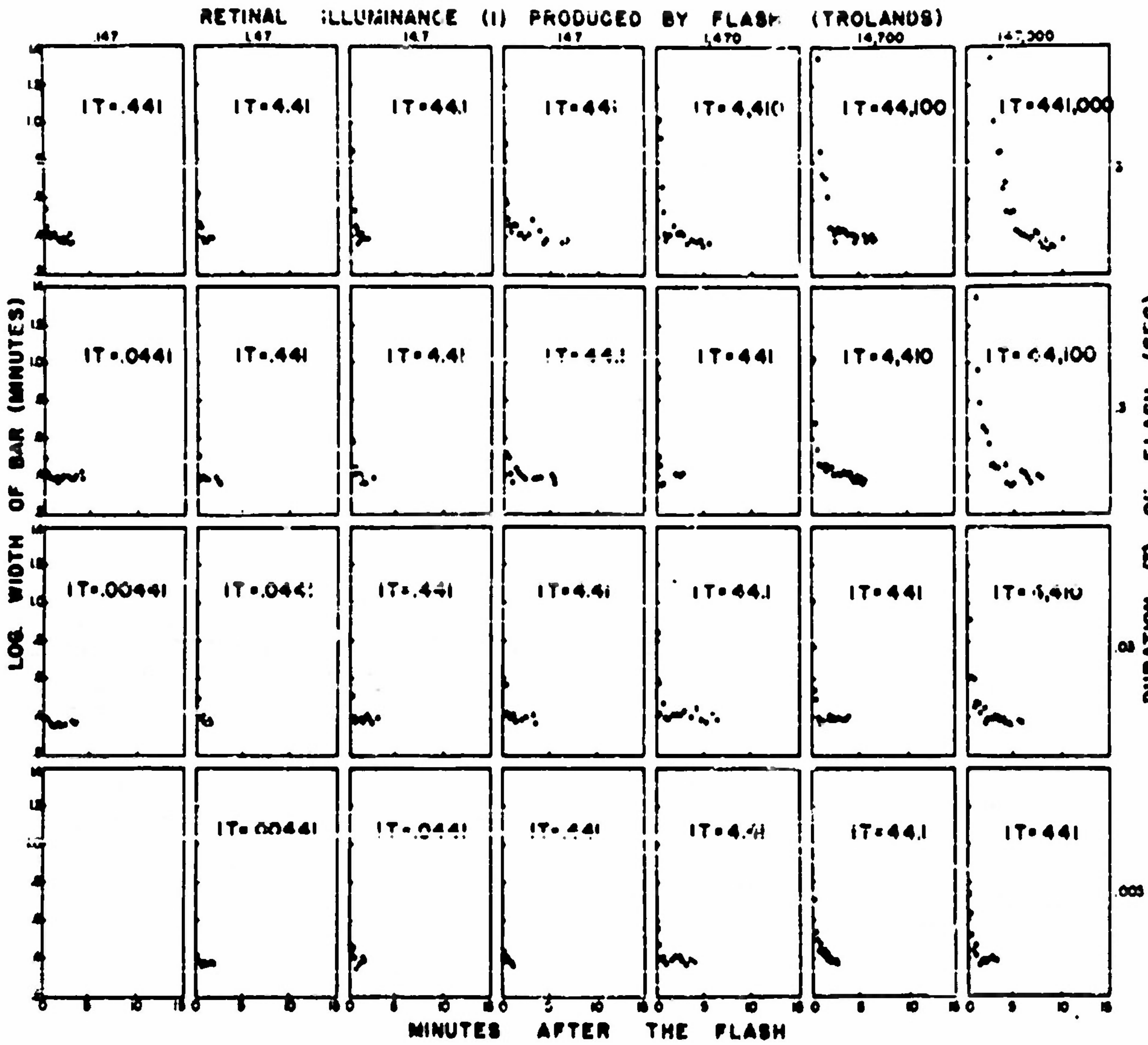


FIG. 9C

DATA FOR L. Z.

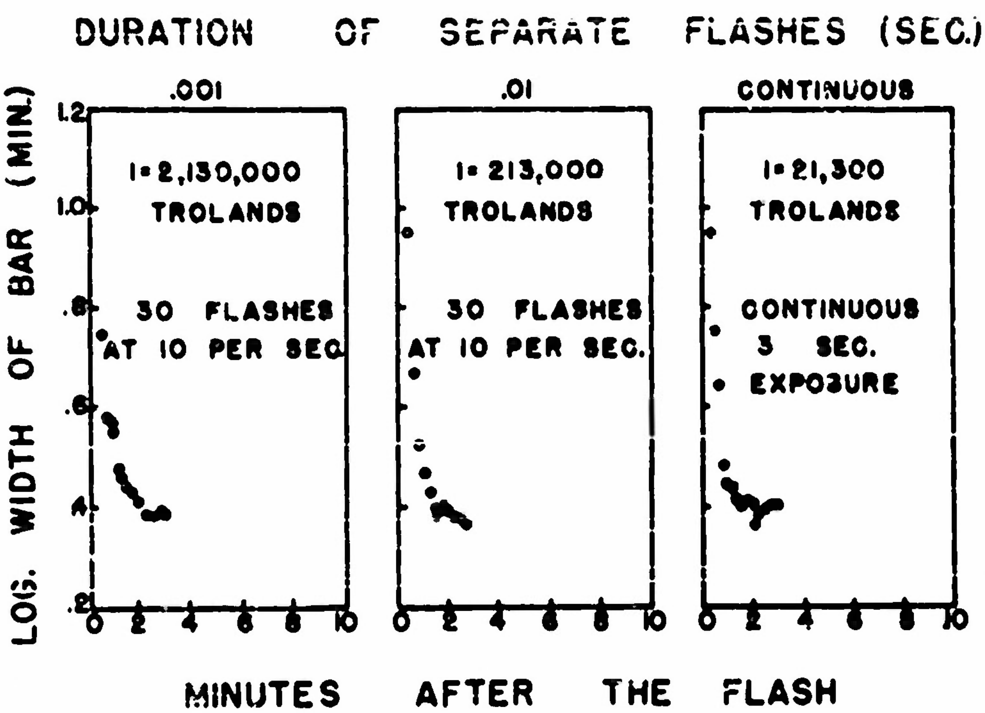


FIGURE 10A

Return of Visual Acuity to Normal Following a Series of 30 Flashes at 10 Per Second and Following Continuous Exposure for 3 Seconds.
(Subject L.Z.)

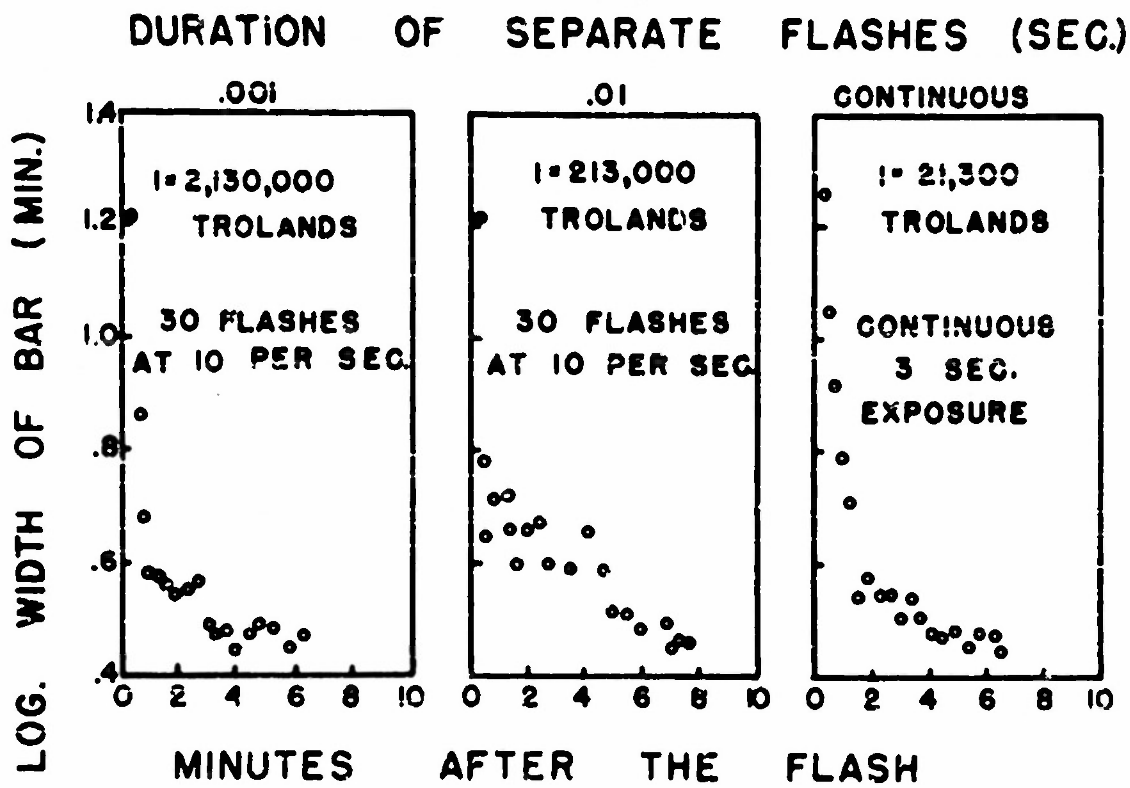


FIGURE 10B

(Subject P.H.)

again until it becomes visible; this is the threshold size that is recorded. From this point on, the procedure is the same as in the case already described.

F. <u>The Recording Mechanism.</u>

The recording mechanism is illustrated in Fig. 3. The recording table with a piece of paper mounted on it moves in the direction of the arrow at a constant rate of 5 mm per minute. Above the moving paper is a metal plate with a small hole D through which a pencil point can be inserted to make a small circle on the record. This plate is attached to a sliding metal bar driven by the flexible cable which is held tight by the weight and is attached to the point E on the non-circular drum. This drum is mounted on the same shaft that drives the target M and the Porro prism which controls the angular size of the bar as seen by the eye. This non-circular drum is designed so that the displacement of the hole D from its starting point D' is proportional to the logarithm of the angular width of the image of the bar. A record of the position of the hole at any given moment can be made by inserting a pencil and tracing around the edge of the hole. The cessation of a flash can be indicated by drawing a straight line along the straight edge which if extended would pass through the center of the hole D.

The data for a 50-minute run can be recorded on a single sheet of paper. Hence the recording table is set in motion prior to the first exposure of the flash patch in any given experimental run and allowed to run for the full 50 minutes. If the session proves to be longer than this the operator takes time out to change to a new sheet of paper and to reset the recording table for a new run.

The graphs presented in this report, showing the return of the threshold width of the bar to normal following exposure to a flash patch, are direct tracings of the records made in the manner described above. In each graph the time scale and the scale representing the logarithm of the width of the bar have simply been added to the trace of the raw data.

Operations such as adjusting the shutter speed, changing the filters, changing the size of the bar and recording the data can all be carried out in total darkness; consequently, during the whole experiment the field of view of the subject is kept in total darkness except for the fixation point, the flash patch and the test patch. If an emergency makes it necessary for the operator to have any light, a small flashlight covered with a red filter is used, and during the time that the light is on the subject is asked to close his eyes. The operator carefully avoids pointing the flashlight at the subject.

SUBJECTS

The data included in this report were obtained from three subjects all of whom were men. Subjects M. A. and L. Z. wore their corrections and subject P. H. did not. The ages and corrections for the different subjects are given in Table 1.

Table 1

Subjects

Subject	Age	Correction (Right Eye)	
M. A.	29	+ 4.75	-1.37 x 5
L. Z.	39	+.25	- .50 x 10
P. H.	22	None	

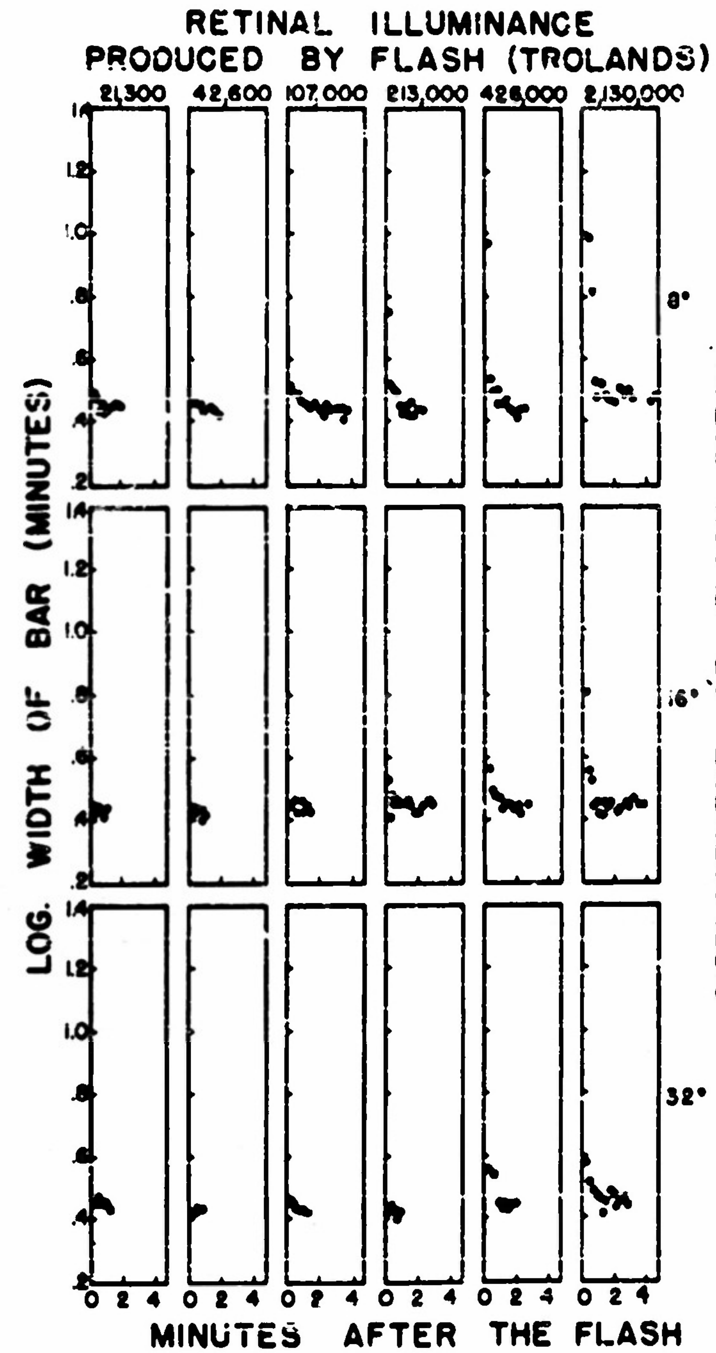


FIG. 11

RETURN OF VISUAL ACUITY TO NORMAL FOLLOWING 1 SEC. FLASHES OF DIFFERENT BRIGHTNESS AND DISPLACED DIFFERENT DISTANCES FROM THE TEST PATCH.
THE FLASH PATCH WAS EXPOSED 1 SEC. AND SUBTENDED A VISUAL ANGLE OF 3.5.°

DATA FOR M.A.

Both authors of this report participated as subjects in the numerous pilot experiments which were conducted during the perfecting of the apparatus and in the determination of the limits which might be set to the variables. Although the senior author did not participate in the final experiments, it may be claimed that the preliminary observations by him showed no trends which differed from those found for other subjects.

Results

A. The Effect of Varying the Duration and Brightness of the Flash Patch When the Flash Patch is Coextensive with the Test Patch.

The results obtained with flashes of various brightness and various durations for the three subjects are presented in Figs. 9A, B and C. The records for different durations at the same brightness level were obtained in a single experimental session for each subject. Records were obtained for exposures of 1, 10, 100 and 1,000 milliseconds as well as for 3, 30, 300 and 3,000 milliseconds, but these data have not been included in the figures because of the convenience in analyzing the results afforded by having both the brightness variations and duration variations in log unit steps. The graphs arranged in diagonal rows sloping from left to right represent constant exposure in the sense that the product of brightness by time is constant. Without a more detailed analysis of the results the conclusion might be drawn that up to 3 sec reciprocity holds between duration and brightness; that is to say, the total exposure is the thing that determines the degree of impairment of the ability to see with the parafovea and also the time required for this ability to return to normal.

B. The Effect of Repetitive Exposures of the Flash Source.

In order to demonstrate the validity of the principle of reciprocity in the case of intermittent exposure, experiments involving a sequence of thirty flashes at a frequency of ten per second were carried out with two observers. The brightness and duration of the separate flashes were varied but the total exposure, that is the product of brightness by duration by the total number of flashes, was kept constant. The results are shown in Figs. 10A and 10B. It can be concluded from this experiment that the reciprocity principle still holds with intermittent exposures.

C. The Effect of Varying the Distance of a Flash Patch from the Test Patch.

Fig. 11 represents the data obtained from one of the subjects showing the effect of varying the brightness and the amount of displacement of a flash patch from the test patch.

On the assumption that the effect produced by a displaced flash patch results from the stray light which produces a veiling illuminance over that region of the retina on which the image of the test patch falls, one can determine from Fig. 9A the brightness of a flash patch which is applied to the same area of the retina as the test patch that produces the same result as the displaced flash patch. This constitutes a measure of the stray light (or veiling illuminance) produced by the displaced flash patch.

It can be noted in Fig. 11 that the effect produced by a one-second exposure of a flash patch 8^{o} from the test patch and producing a retinal illuminance of 107,000 trolands is approximately the same as for one 16^{o} from the test patch and producing 426,000 trolands or one 32^{o} from the test patch and producing 2,130,000 trolands. Furthermore, as can be observed in Fig. 9A this effect is equivalent to that produced by a one-second exposure of a flash patch superimposed on the test patch and producing a retinal illuminance of 44.1 trolands.

These facts are presented graphically in Fig. 12, which shows the displacement and retinal illuminance of flash patches (3.5° in diameter) that produce a veiling illuminance of 44.1 trolands over the image of the test patch.

Moon and Spencer,[1,2] on the basis of the data of Holladay[3] and Stiles[4], have recommended the use of the following equation for computing the veiling brightness (B_V) at one part of the field of view produced by a patch of brightness (glare source) in a different part of the field.

$$B_V = k\,\theta^{-n}E = k\,\theta^{-n}B_G\,\omega\cos\Psi \tag{7}$$

where k and n are constants and are equal to 10 and 2 respectively. θ is the angle in degrees between the center of the test patch and the center of the flash patch; E is the illumination in the plane of the pupil produced by the glare source; ω is the solid angle in steradians subtended by the glare source, B_G is its brightness, and Ψ is the angular deviation of the pupillary axis from the glare source. This equation does not hold for values of θ smaller than 2°.

Since, in the case in hand, the beams of light from both the test patch and the flash patch are restricted and enter the eye without interference from the natural pupil, the term $\cos\Psi$ which allows for the obliquity of plane of the natural pupil may be dropped. Furthermore, in computing retinal illumination (I) the term $\cos\Psi$ may be ignored in the case of restricted beams so that the equation,

$$I = B\,A\cos\Psi, \tag{8}$$

where A is the area of the natural entrance pupil in sq mm, B the brightness in c/m^2, and Ψ the angular deviation of the pupillary axis from the patch of brightness, reduces to

$$I = B\,A \tag{9}$$

where A represents the area (sq mm) of the cross section of the entering beam at the center of the entrance pupil.

Expressed in terms of retinal illuminance, Equation (7) becomes

$$I_V = I_F\,\omega\left(\frac{k}{\theta^{n}}\right) \tag{10}$$

where I_V is the veiling illuminance produced by stray light covering the image of the test patch, I_F is the retinal illuminance in the image of flash patch, and ω is the solid angle subtended by the flash patch. As applied to the set of data in Fig. 12 the solid angle subtended by the 3.5° flash patch is 0.00298 steradians and the value of I_V is constant at 44.1 trolands and hence, if as assumed by Moon and Spencer that k = 10 and n = 2, then

$$I_F = \frac{(44.1)\qquad \theta^2}{(10)\qquad (.00298)} = 1470\ \theta^2. \tag{11}$$

The straight line in Fig. 12 is a plot of this equation.

The agreement with the actual data is not perfect, but is good enough to justify the use of Equation (7) for computing the effect of a displaced flash patch upon the subsequent visibility of a dark object against a night sky background.

In accordance with the basic idea that the effect produced by a displaced flash patch is mediated by stray light in the eye, the effects of two or more separate flash patches may be considered to be strictly additive, and hence Equation (10) may be used in deriving a general equation for computing the stray light at any given point of the retina produced by any distribution of brightness in the field of view.

$$I_V = k\int_0^{\theta'}\int_{\phi_1}^{\phi_2} f(\theta)B \cos\Psi \sin\theta \, d\phi d\theta \qquad (12)$$

where $f(\theta) = (57.3\theta)^{-2}$ when θ is expressed in radians and is greater than 0.035. In this equation I_V is the veiling illuminance at a given point P' on the retina corresponding to a given direction OM in the visual field, B is the brightness in any given direction OP which makes an angle θ with OM and has a meridional displacement ϕ from the zero half-meridian through the axis OM. Ψ is the displacement of the pupillary axis from OP. ϕ_1 and ϕ_2 represent the limiting values of ϕ for a given zone θ radians from OM for which the value of Ψ is less than $\pi/2$. θ' is the value of θ for the largest zone at one part of which the value of Ψ is still not more than $\pi/2$.

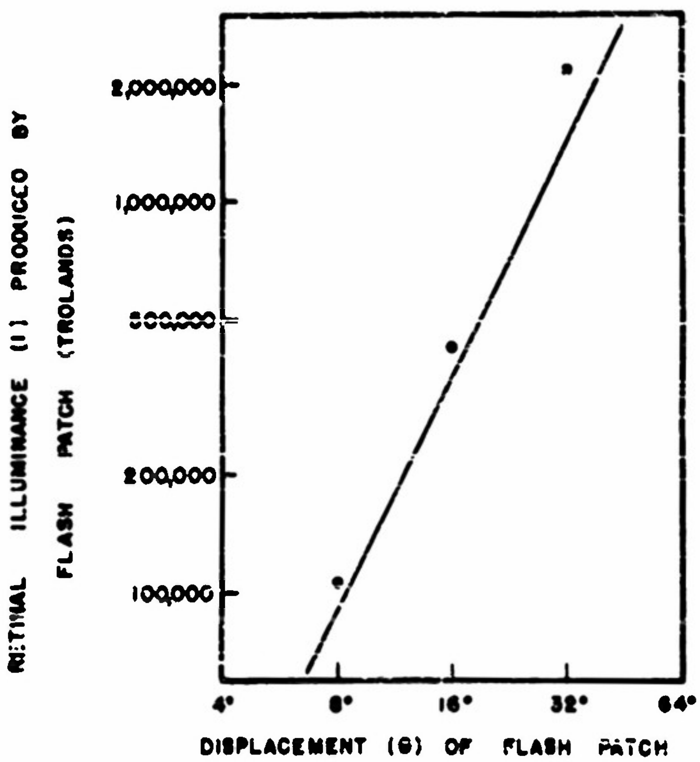


Figure 12. Retinal Illuminance (I_F) Produced by a Flash Patch 3.5° in Diameter and Displaced at Various Angles (θ) From the Center of the Test Patch Required to Produce a Veiling Illuminance of 44.1 Trolands.

Equation 12 cannot be used to determine the contribution which is made by the part of the field centered at P and extending out 2°, because the form of the function $f(\theta)$ is not known for values of θ less than 2°. Further study of this problem needs to be made. In applying this equation to the problem at hand, allowance must be made for the changes in pupil size that occur during and subsequent to the flash.

D. The Effect of Varying the Area of the Displaced Flash Patch.

Holladay, Stiles and others have all recognized the importance of the role played by stray light in evaluating the effect of a patch of brightness in one part of the field of view upon the ability to see in another part of the field, but have not been willing to ignore completely the possibility that there may be some interaction between the different parts of the retina by way of nervous mechanisms. Moon and Spencer have also been cautious on this point but have tentatively accepted the proposition that whatever mechanisms exist behave as if the whole effect were mediated by stray light. It is important, therefore, to demonstrate by whatever methods possible that the phenomena do behave as if mediated by stray light and whatever evidence, be it direct or indirect, that bears upon this point ought to be brought forth to add confidence in the basic principle involved in Equations 7 and 12.

If the effect produced by a displaced flash patch is mediated by stray light, then the effect of varying the area of the patch should be completely akin to varying the brightness of the patch. In order to demonstrate the extent to which this relationship does hold, experiments have been carried out in which the brightness and area of a displaced patch have been varied. The results of this sort of experiment for three subjects are presented in

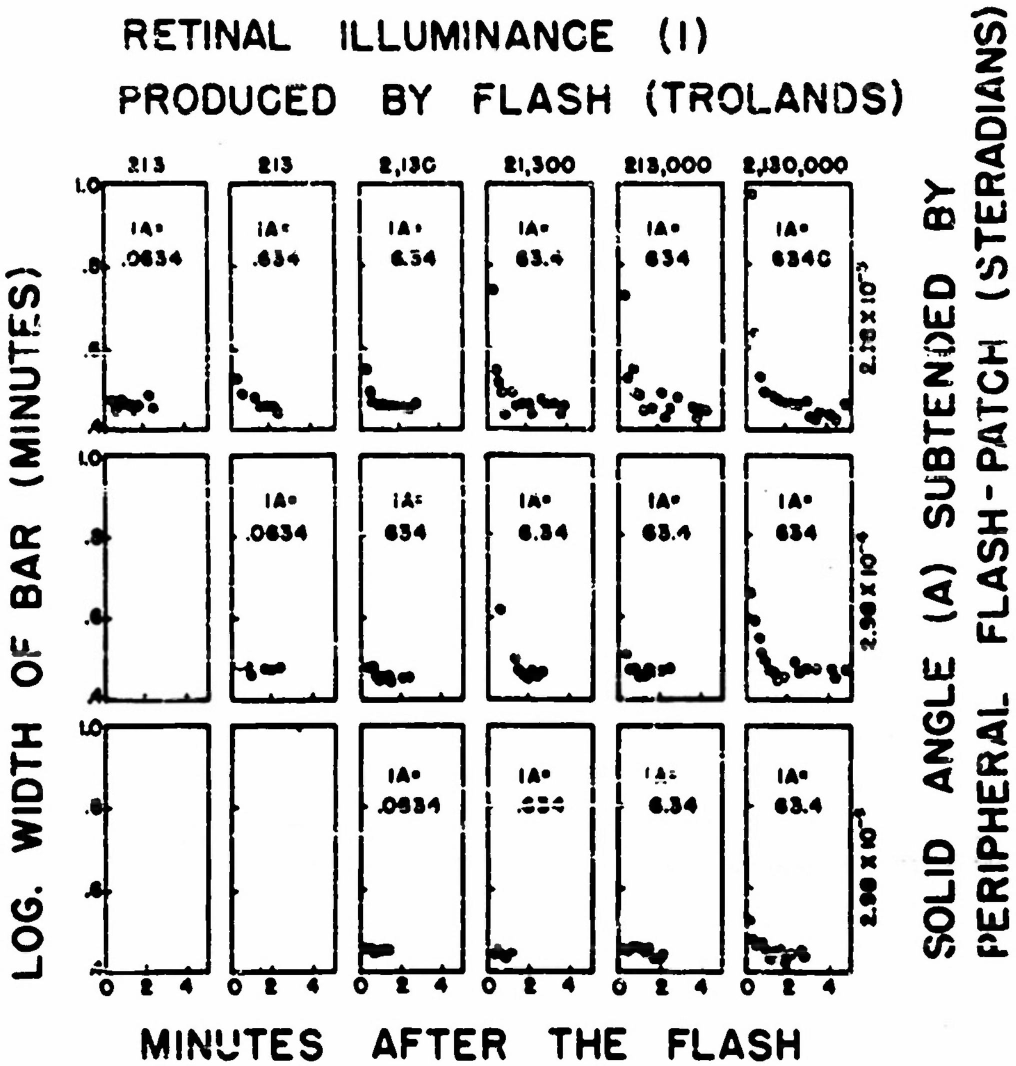


FIG. 13A

RETURN OF VISUAL ACUITY TO NORMAL FOLLOWING EXPOSURE OF A FLASH PATCH DISPLACED 8° FROM THE CENTER OF THE TEST PATCH AND HAVING VARIOUS ANGULAR SIZES AND BRIGHTNESSES.

DATA FOR P. H. THE DURATION OF THE EXPOSURE WAS 3 SECONDS.

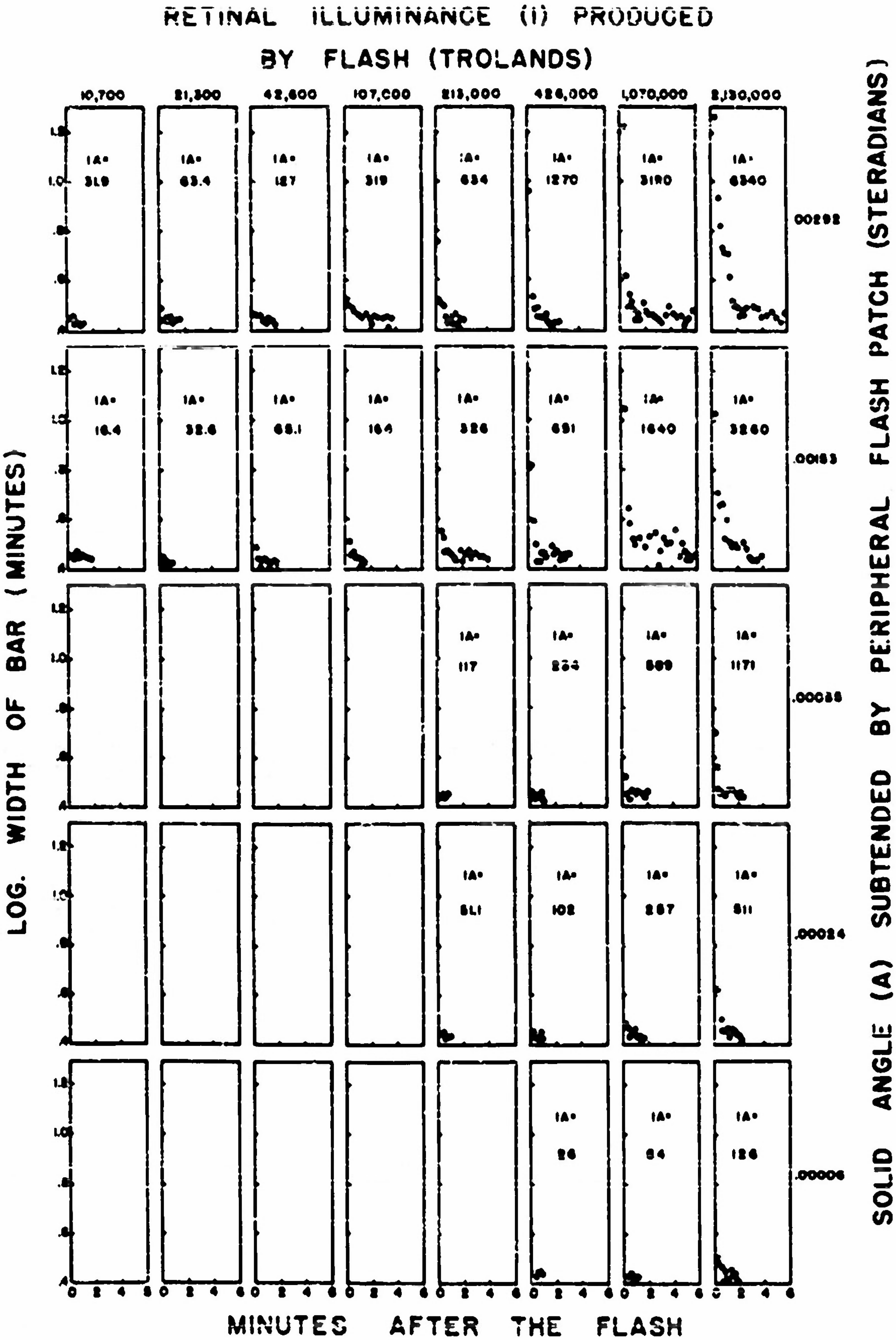


FIG. 13C

DATA FOR M.A.

THE DURATION OF EXPOSURE WAS 1 SECOND.

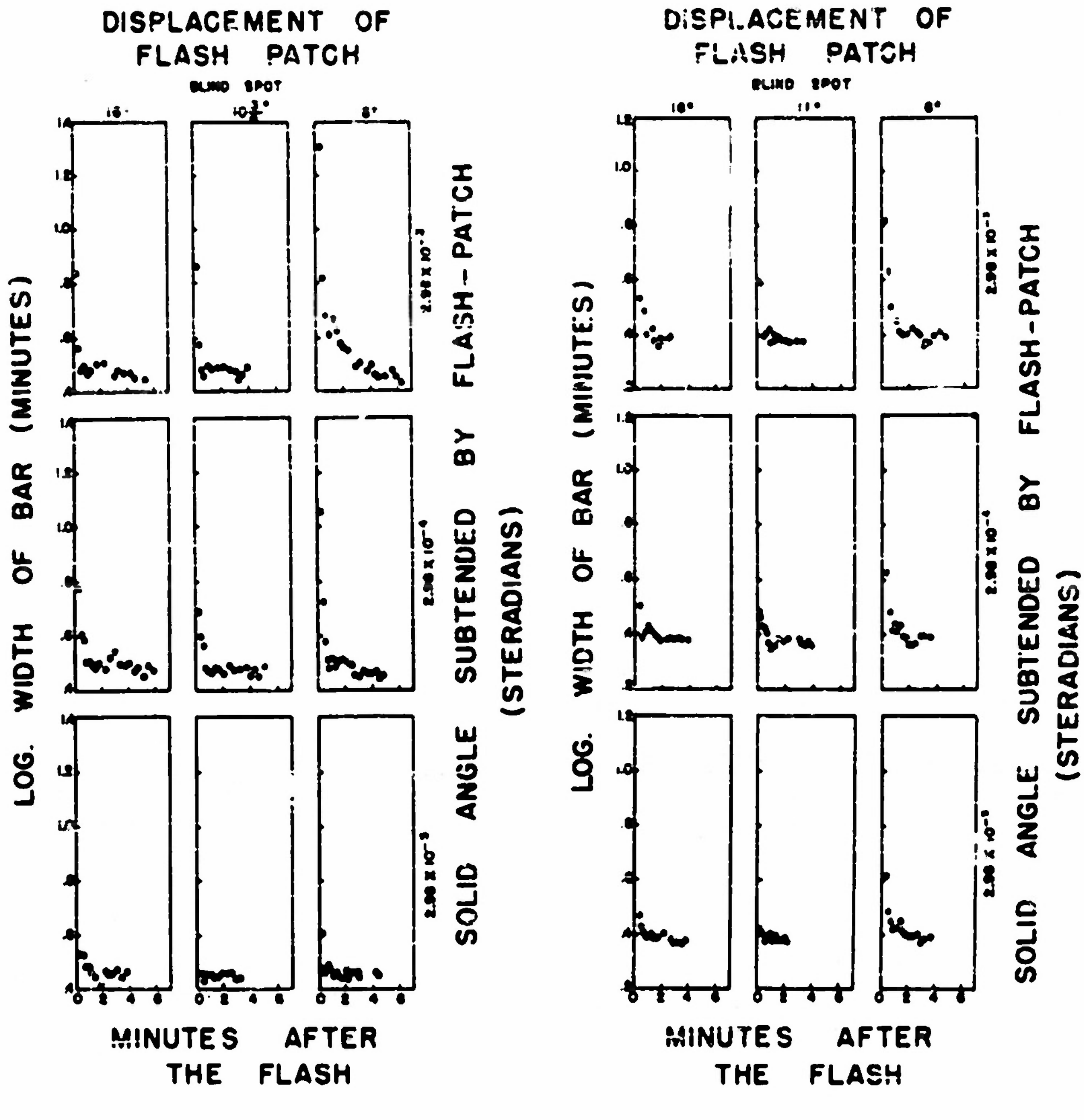


FIG. 14

RETURN OF VISUAL ACUITY TO NORMAL FOLLOWING A 3 SECOND EXPOSURE OF A FLASH PATCH HAVING VARIOUS SIZES, AND APPLIED TO THE BLIND SPOT, AND TO THE RIGHT AND LEFT OF IT.

THE PATCH PRODUCES A RETINAL ILLUMINANCE OF 2,130,000 TROLANDS.

Figs. 13A, 13B, and 13C. In the case of subjects P. H. and L. Z., the area as well as the brightness was varied in log unit steps; consequently, diagonal rows of graphs sloping from left to right represent products of area and brightness which are constant. In the case of subject M. A., different steps were used in varying the area; consequently, the analysis is somewhat more difficult by casual inspection. If anything, the effect of varying the area appears to be somewhat more effective than varying brightness, but the difference is probably not significant and it may be concluded that the effect of a displaced flash patch is mediated by stray light or some equivalent mechanism.

E. The Effect of a Flash Patch which Falls in the Blind Spot.

In Figs. 14A and 14B a comparison is made, in the case of two subjects, of results obtained with flash patches that fall in the blind spot and to the right and left of the blind spot. The flash patch to the left of the blind spot is of course closer to the test patch, and consequently the effect is much more pronounced than in the case of the flash patch on the right. The important thing is that the effect produced by a flash patch falling in the blind spot is intermediate between that produced by a flash patch on either side, at least at the higher brightness levels. This indicates that little is added by having an active retina underneath the image of the flash patch. In other words, in this sort of phenomenon the retina acts purely as a reflector.

With the heads of the subjects mounted in the instrument, the blind spots were mapped out with the subjects fixing the fixation point and with the targets for mapping the blind spot kept in the plane of the aperture A'_4. In this way it was possible to demonstrate directly that the displaced flash patch fell within the blind spot when placed 11° from the center of the test patch in the case of P. H. and 10 3/4° in the case of L. Z. The test patches in relation to the blind spots are shown in Fig. 15.

F. The Effect of Using Flash Patches Larger then the Test Patch.

In general one expects the adaptation of the eye to be a function of the adaptation of photoreceptors within the eye, and consequently if one were to increase the diameter of the flash patch from 8° to 16° or 32°, it would not be expected that this increase in area of the flash patch would affect the adaptation of that region of the retina which receives the image of the test patch except insofar as the total amount of the stray light in the eye would be increased. The total increase in stray light (veiling brightness) at the center of the flash patch resulting from an increase of its diameter from 8° to 16° is equivalent to only 1.3% of its brightness

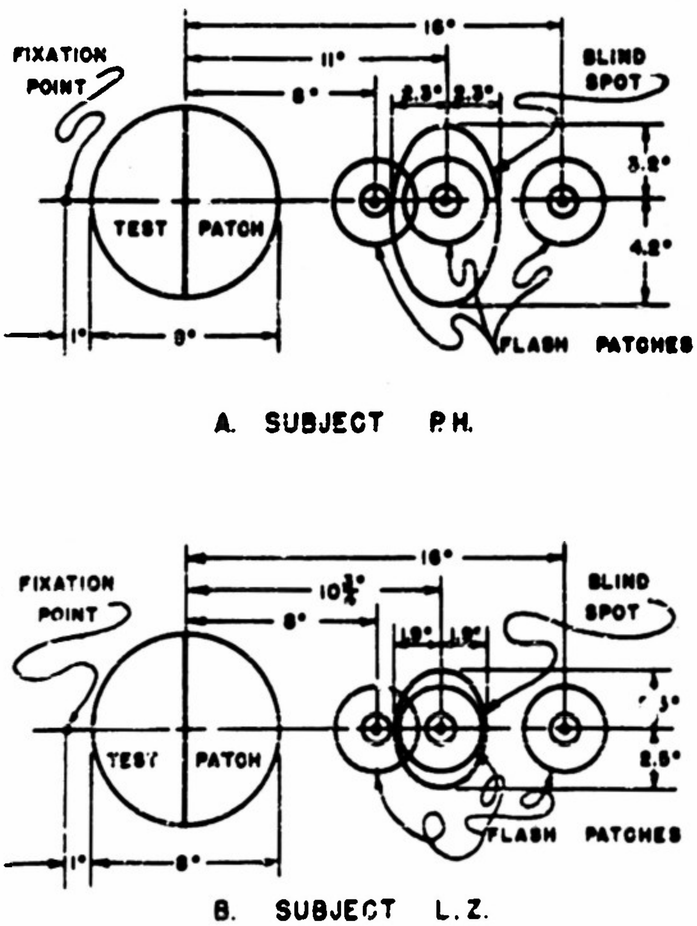


Figure 15. Location of the 0.35°, 1.11° and 3.5° Flash Patches With Reference to the Blind Spot Which Were Used in Acquiring the Data in Figure 14.

and a further increase in area to 32° would further increase the amount of veiling brightness only 0.4% of the brightness of the flash patch.

As a matter of fact, Wright[5] has already demonstrated that the adaptation at a given part of the retina produced by direct exposure to a patch of brightness is not measurably affected by the area of the patch.

It appears to be worthwhile, however, for reasons already stated to demonstrate if possible that this principle operates under the conditions of the present series of experiments. Consequently, an experiment was devised in which the area of a flash patch concentric to the test patch was made 8°, 16° and 32° in diameter, respectively.

A special type of exposure device was necessary for this phase of the investigation. This device, illustrated in Fig. 16, is completely separate from the major instrument described above (Fig. 3). It is necessary, therefore, for the subject to bite the biting board of the flash patch exposure device (Fig. 16) in order to have the flash patch exposed to him and then he switches to the biting board of the major instrument in order to observe the test patch.

The head is fixed in space by means of a forehead board and a biting board so that the entrance pupil of the right eye falls at the point E. The lenses L_2 and L_3 constitute a Ramsden type eye piece which focuses an image of the aperture A_1 in the plane of the entrance pupil. P_1 is a beam splitter. Behind the aperture A_1 is a piece of milk glass and a 7.5 watt incandescent bulb, S1. The aperture A_1 constitutes an aperture stop. Its image in the plane of the entrance pupil of the eye is 2 mm in diameter. The point of fixation is the aerial image at A4 of the small pin point aperture A_3 formed by the lens L_1. This point of fixation is seen at an angular distance of 5° from the center of the aperture A_2. When the aperture A_2 subtends a visual angle less than 10°, it is necessary to put a second small aperture in the same diaphragm at A_4 in order to permit the image of A_3 to be seen at A_4. When A_2 subtends a larger visual angle than 10°, the second aperture is unnecessary. Apertures at A_2 subtending visual angles of 8°, 16° and 32° have been used. The duration of exposure was approximately 3 seconds. The source S_1 was turned on and off by a microswitch activated by a revolving cam driven by a constant speed motor.

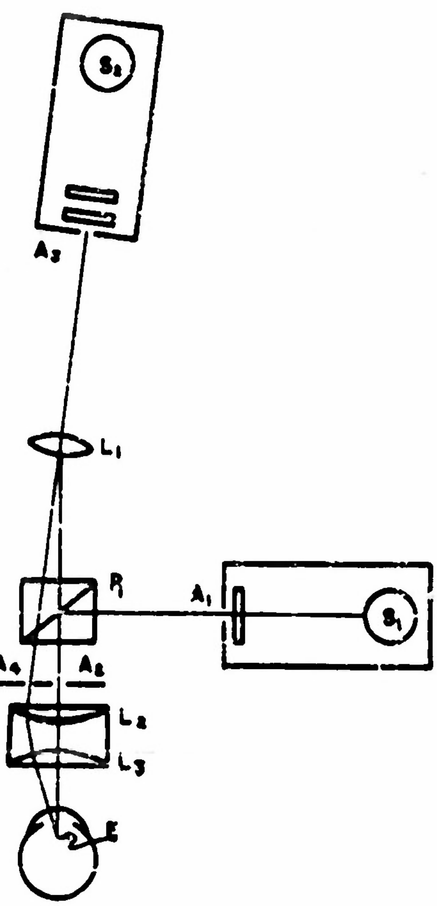


Figure 16. Apparatus for Presenting Large Flash Patches to the Eye.

The procedure in carrying out the experiment was as follows. The forehead rests and biting boards of the two instruments were adjusted so that the entrance pupil of the right eye would fall at the proper points. After 30 minutes of dark adaptation, the subject bit the biting board of the major instrument and fixated the fixation point steadily. The operator started the recording apparatus, and several determinations and recordings of the threshold width of the bar were made. The subject then bit the biting board of the exposure device and the fixation point steadily while the operator turned on the motor which drove the cam that gives a 3-second exposure. He marked the cessation of the flash on the record. The subject then moved back over to the major instrument for measuring the threshold width of the black bar, bit the biting board, and than fixated the fixation point. The operator, starting with the smallest width of the bar, gradually increased the width of the bar until the bar became visible and then recorded the size of the bar on the recording apparatus. This process was repeated until the threshold width of the bar returned to normal. The experiment was than repeated using a 16° flash patch, and after the effects of this flash patch had worn off, the procedure was repeated using a 32° flash patch.

The results (Fig. 17) indicate that the effect produced is somewhat more pronounced with the larger flash patches. Insofar as the results do differ for flash patches of different size they are in variance with the results previously described. Eye movements and the role played by the border of the positive after-image might account for part of this discrepancy.

G. The Effect of a Flash Patch in the Case of a Test Patch with a Lower Background Brightness then 0.01 Millilambert.

It was intended at the outset of this investigation to explore the effects of bright flashes using a background brightness of 0.0002 millilambert and a 2 mm artificial pupil. However, in exploratory experiments dealing with this problem, it was soon discovered that in the case of three subjects not even the 8° test patch could be differentiated from its dark background at this low level of brightness. The question remained, however, as to what is the lowest level of brightness at which visual acuity measurements can be made, and whether it takes any longer to recover from a flash of light at this lowest level as compared with a background of brightness of 0.01 millilambert. In order to study this phase of the problem and in order to determine the lowest level at which visual acuity measurements might be made, the following experiments were performed.

Subject L.Z. was dark adapted for 30 minutes and then exposed to a flash patch superimposed upon the test patch for one second. The brightness of this flash patch was such as to produce a retinal illumination of 14,700 trolands. Following the flash, the recovery of visual acuity was measured in the normal manner using a background brightness producing 0.107 troland. The only deviation from the usual

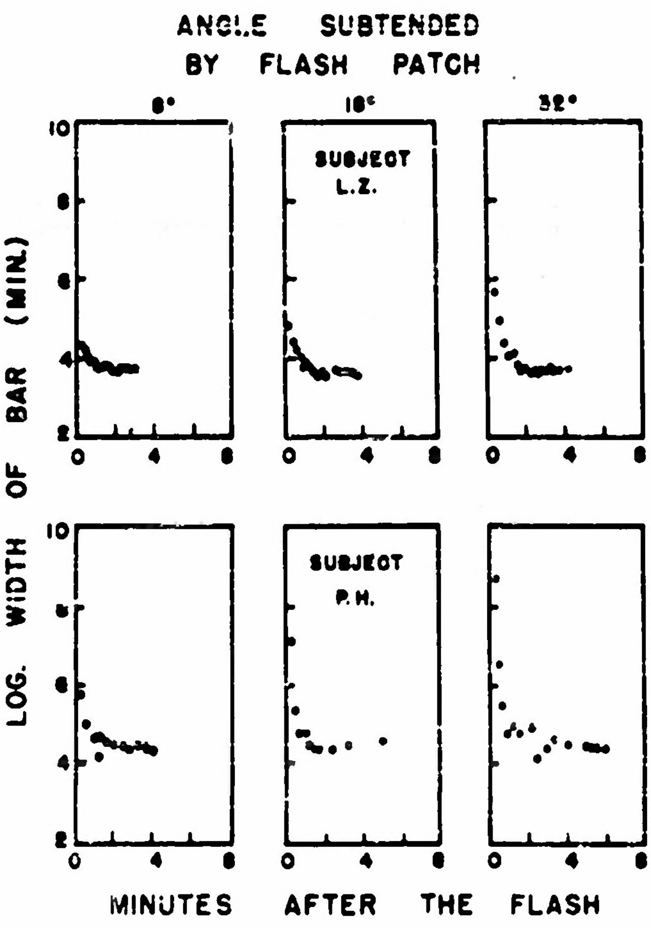


Figure 17. Return of Visual Acuity to Normal Following a Three-Second Exposure to a Flash Patch Producing 101.5 Trolands of Retinal Illuminance Placed Concentric to the Test Patch and Having Various Angular Sizes.

procedure was that a one-mm vertical line was used which provided a range of visual angles from 4 to 64 minutes. When it appeared certain that the visual acuity had reached a constant level, the brightness of the test field was dropped by means of a variac to a brightness level producing 0.049 troland and a series of visual acuity measurements were made to trace the process of dark adaptation to this lower level. After the visual acuity measurements had leveled off at this brightness level, the brightness was dropped again to a level producing 0.024 troland and another series of visual acuity measurements was made. An attempt was then made to repeat the process at brightness levels producing 0.011 troland and 0.005 troland. At this last level not only was the bar invisible but also its background could not be differentiated from the surround. Following this the brightness was raised back again through the same steps to the level of 0.107 troland and at each level a series of threshold widths was determined. The data for this experiment are plotted in Fig. 18A.

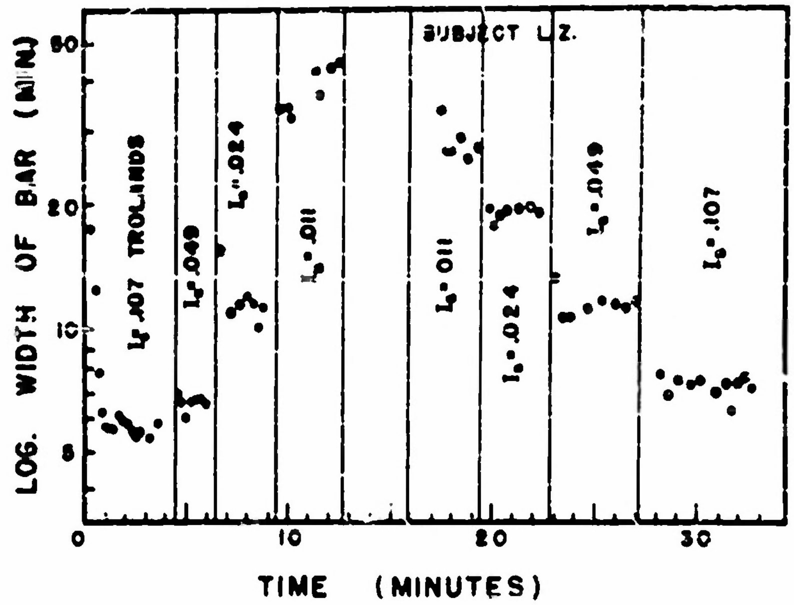


Figure 18A. Visual Acuity Measurements at Various Brightness Levels Made in the Sequence Indicated. Zero on the Time Scale Indicates the End of a One-second Flash Which Was Coextensive with the Test Patch and which Produced a Retinal Illuminance of 14,700 Trolands.

The same sort of experiment was carried out for subject P.H., except that following the 30 minutes of dark adaptation, the bright flash was omitted and the subject proceeded immediately to make a series of visual acuity measurements at a retinal illuminance level

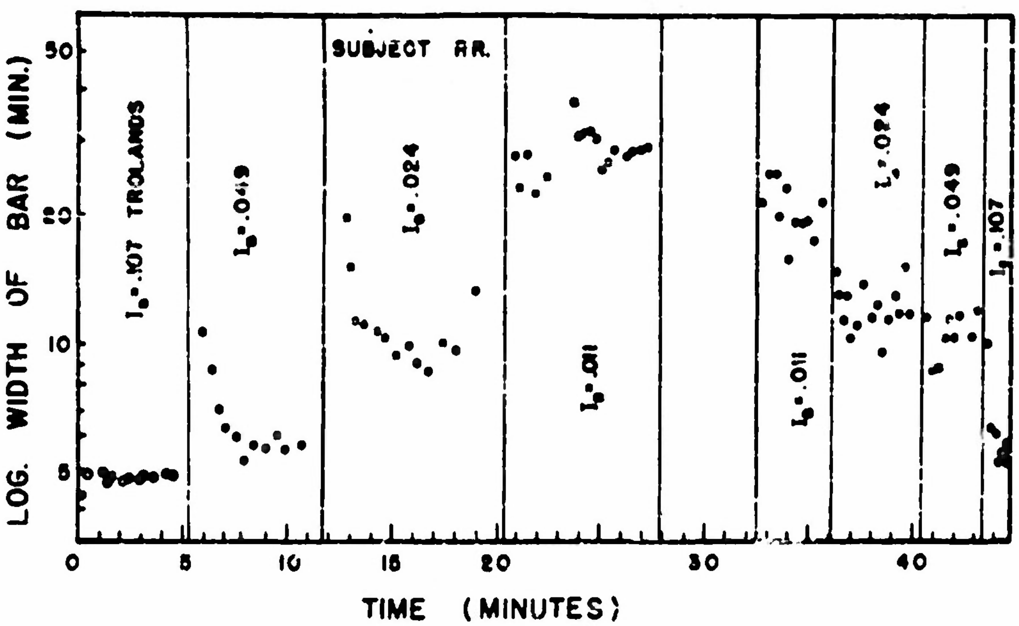


Figure 18B. Visual Acuity Measurements of Various Brightness Levels Made in the Sequence Indicated. This Series of Measurements was Preceded by 30 Minutes of Dark Adaptation.

of 0.01 troland. The remainder of the experiment was carried out in the same way as for the subject L. S. The data are shown in Fig. 18B.

The data for P. H. indicate that when the level of the retinal illuminance is dropped to a lower level, a short period of time is required to dark adapt to this lower level. Only one instance of this sort of thing is found in L. Z.'s record; namely, when the level of retinal illuminance was dropped from 0.049 to 0.024 troland. The data in the second half of the experiment for each subject were analyzed by averaging at each retinal illuminance level the threshold widths of the bar and then plotting these average widths as indicated in Fig. 19. These data explain why visual acuity measurements cannot be made at lower levels of retinal illuminance. At a level of 0.005 troland the width of the bar can be extended indefinitely without reaching a threshold value. These data are in agreement with the data of Hecht and Mintz[7], who also used a dark bar on a uniform background for measuring visual acuity at low levels of retinal illuminance.

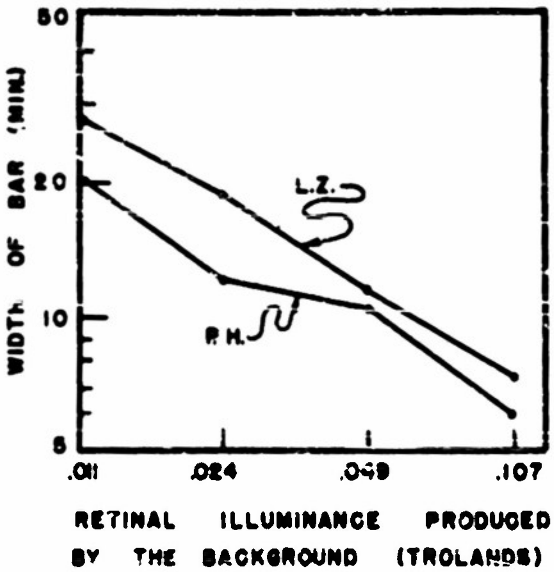


Figure 19. The Effect of Brightness Level Upon the Threshold Width of the Bar.

THEORETICAL CONSIDERATIONS

A. <u>The Advantages and Limitations of the Visual Acuity Method of Measuring Dark Adaptation.</u>

One feature of this method is that in tracing the course of dark adaptation, the retina is constantly exposed to the level of retinal illuminance toward which it is becoming adapted.

When the flash is very bright and the duration long, it is not possible to trace the course of dark adaptation during the period immediately following the flash. There is an upper limit beyond which increasing the width of the bar does not improve its visibility, and this is the thing which limits fundamentally the extent to which the course of dark adaptation can be traced by the visual acuity method during the early phases of the process.

In the case of foveal vision, where the number of ganglion cells in the retina is sufficient to provide each photoreceptor with its own private pathway up the optic nerve, the blurredness of the retinal image is the primary factor which determines the relationship between the width of a bar and its visibility. However, in the case of peripheral vision where the number of ganglion cells is much smaller than the number of photoreceptors, a large number of photoreceptors must converge upon a single ganglion cell and area summation can be expected to be a factor.

The data in Figs. 18A and Fig. 18B and in Fig. 19 indicate that increasing the width of the bar up to 40 minutes of arc improves its visibility.

It would have been possible to continue this experiment by using bar widths exceeding those used and varying the brightness of the background to measure the threshold. In this way one could trace the experiment to bar widths which yield constant thresholds.

At any given level of background brightness this problem could be studied by varying both the contrast and the size of the bar.

B. The Form of the Curve to be Used to Represent the Data.

No attempt has been made at the theoretical level to determine the type of curve which ought to be used to fit the data showing the recovery from a flash. It involves not only the relationship between the photochemical process in the rods and the discharge of impulses, but also the mechanisms of interaction between the retino-cortical pathways which determines whether a border is seen or simply washed out. It is hoped that it will be possible later to undertake this sort of analysis of the data.

The problem is made somewhat easy by the fact that the measurements are all made with a background brightness producing a retinal illuminance of 0.01 troland or less, and at these levels only rods are involved.[6]

C. The Use of a Long Narrow Bar for Measuring Visual Acuity.

Attention should be drawn to the advantage of using a long dark bar on a uniform field. In the first place, it makes it easy to assess the role played by spatial summation between the retino-cortical pathways. In the second place, it is easy to relate the visibility of such a test object to the visibility of a straight border separating bright and dark areas. As a matter of fact, as the width of the bar is increased, the problem eventually becomes transformed into one of the visibility of a border separating dark and light areas. In the third place, the mechanism of interaction between retino-cortical pathways which is involved in determining the visibility of the border is much easier to visualize and analyze when a straight border is used as compared to a curved one such as is encountered with a circular test object.

D. The Role Played by Eye Movements.

Eye movements undoubtedly impair the precision of the data in the kind of experiments described above. Under the conditions of these experiments it is very difficult to maintain steady fixation, and this might cause considerable variation from reading to reading.

E. The Psychophysical Method.

The method employed for measuring the threshold, which involves bringing the size of the target from the sub-threshold width to the threshold of visibility and which depends upon the subject's ability to determine when the bar is at the threshold of visibility, leaves a good deal to be desired. A more effective technique can no doubt be devised, but would require more elaborate apparatus and much more time both in acquiring the data and in analyzing it. It was not felt that extreme precision was the major objective, and it is believed that the data acquired do provide satisfactory answers to the problems which were to be solved.

F. Positive After Images.

A complete theoretical interpretation of the data in this report must involve consideration of the positive after image produced by the flash as well as the depletion of the available photosensitive substance in the photoreceptors.

SUMMARY AND CONCLUSIONS

This investigation has succeeded in demonstrating the operation of three basic principles which can be used in predicting the effect of a flash upon the subsequent ability of an eye to see dark objects against a night sky background.

(1) The adaptation of any given part of the retina can be regarded as being independent of adaptation processes in other parts of the retina.
(2) Reciprocity between time and intensity can be assumed to hold at least over a three-second interval.
(3) The effect of a flash displaced from that part of the retina which is used in viewing an object can be accounted for in terms of stray light. The amount of stray light falling at any given part of the retina can be computed from the Stiles-Holladay equation. (Equations 7 and 12).

It is true that the constants and perhaps the form of Equation (7) need to be further verified in order to give more confidence in the use of this equation for engineering purposes. It is already known that the form of this equation will have to be modified for small values of θ. It is believed, however, that a more direct method than the one used here can be used for determining these constants and the best form of the equation, since this method simply demonstrates the operation of the basic principles at low levels of illuminance. Therefore, the repetition of these particular experiments with a larger number of subjects hardly appears to be in order.

The most basic set of data needed for engineering purposes for the problem at hand is the set of data illustrated in Figs. 9A, 9B and 9C, which show the effects of flashes of different brightness and duration.

Since it is shown in these figures that a reciprocity exists between duration and brightness, a single set of curves such as the top row of curves in each figure representing effects for various values of IT would suffice. It would undoubtedly prove of considerable value to have a set of curves which fit the data and which can be expressed in terms of equations. Such a reduction of the data to a set of equations has not yet been attempted. For engineering purposes it might appear sufficient at first sight to select curves which fit the data without reference to the theoretical significance. The limitation to such a procedure is that curves fitted in this way cannot be extrapolated very far beyond the actual conditions of the experiments. Curves which express basic principles give more freedom in this direction.

The data in Figs. 9A, and C apply to a background of 0.0107 troland. Sets of curves for various values of IT and background brightness should be available in order to make calculations for any level of sky brightness.

The lowest level of background brightness at which visual acuity measurements can be made is one which produces approximately 0.01 troland of retinal illuminance.

In applying data obtained with dark bars on a uniform background to practical situations, it must be kept in mind that the visual acuity measured by this type of target is better than that obtained by almost any other type of target, for example, by a pair of bars or a Landolt C or a dot, or a letter. Consequently, allowance for this difference must be made when using data obtained with a single narrow bar in attempting to predict the effect of a flash of light upon the visibility of targets of a more complex configuration. At low levels of retinal illuminance, one is concerned primarily with the detection of large objects, and for this purpose the data obtained with long narrow bars apply directly.

In this study we have dealt with large patches of brightness uniformly distributed in the field of view, or with displaced patches which produce an indirect effect through stray light which is uniformly distributed over the retina. If the region of the retina used for viewing an object is previously exposed to a finely articulated pattern involving sharp high contrast borders, this chopped up pattern of adaptation introduces a complication which has not been considered in this study.

BIBLIOGRAPHICAL REFERENCES

1. Moon, P. and Spencer, D. E., J. Opt. Soc. Am., 35, 233-248 (1945).

2. Moon, P. and Spencer, D. E., J. Opt. Soc. Am., 33, 444-456 (1943).

3. Holladay, L. L., J. Opt. Soc. Am., 12, 271-319 (1926).

4. Stiles, W. S. and Dunbar, C., Illum. Res. Com. (Great Britain) Tech. Paper No. 16 (1935).

5. Wright, W. D., Researches on Normal and Defective Colour Vision, St. Louis, 230-231 (1947).

6. Steinhardt, J., J. Gen. Physiol., 20, 185-209 (1936-37).

7. Hecht, S. and Mintz, E. U., J. Gen. Physiol., 22, 593 (1939).